The Nature of Reality

Michael Redhead
Wolfson College, Cambridge

Ever since the early days of the Scientific Revolution, the world described by science has been very different from the commonsense world of everyday experience. The world of the physical sciences is a world of entities endowed with the 'real' or primary qualities of mass, figure, motion, etc, a world devoid of the richness of human experience, the colours, tastes and smells we are all familiar with. These are the secondary qualities that are elicited by a long chain of cause and effect, originating in the external world imbued just with the primary qualities. Eddington summed up the situation with his famous 'two tables', the one he sits at as he writies, solid, impassive, and the table of modern physics, mostly empty space with myriads of rapidly moving particles. Eddington was roundly attacked by the philosopher, Susan Stebbing, for, among other things, daring to suggest that the 'scientific' table was more real than the 'ordinary' table. But of course Stebbing's arguments on this score would not convince the latter-day scientific realists, who take scientific statements as expressing, ~~in some sense~~, ~~literal~~ putative truths about the world; not truths that are known indubitably, but ~~again~~ in some sense, warranted as scientifically acceptable, in the light of empirical adequacy, depth, coherence, unifying power and other desirable features of scientific theorizing. Such a realist stance is, of course, controversial, but I am going to assume it for our present purposes and seek to pursue the nature of Eddington's scientific table a little further than he took it himself.

What about the 'particles' I said the table was made up of? At one level of description they are the atoms and

molecules of the chemist, but at a closer level of description these are composite entities made up of still smaller 'bits', the electrons, protons and neutrons. But again we can pursue the analysis, seeing the proton and neutron as themselves made up of other particles, the so-called quarks and gluons. Then there are the particles of light, the photons, which in some way mediate electromagnetic interactions in the same way that the gluons mediate the strong nuclear forces. Particle physics has catalogued a considerable variety of these fundamental entities, tied together in unified symmetry schemes of ever greater generality. What are these particles supposed to be like? On some accounts they are literally points imbued with mass, electrical and other charges that govern the scale of their interactions. On other accounts they are to be thought of as excitations of a field, as processes rather than enduring substances. And most recently they have come to be thought of as very small pieces of string wriggling around in space and time, but in some, still largely mysterious way, constitutive of the space and time in which they wriggle!

All this is very interesting and relevant to the title of this lecture, but it is not what I am going to talk about today. Whatever the ultimate nature of these atomic and subatomic entities, they are all supposed to obey a new type of mechanics called quantum mechanics, which seems on the face of it, quite different from the familiar Newtonian mechanics that governs the motion of large-scale objects such as billiard balls, or indeed tables! It is this mysterious new type of mechanics that I want to talk about. I will continue to refer to 'particles', but without prejudice as to their detailed intrinsic nature.

Quantum mechanics allows these particles to have properties, but with certain queer reservations. In the first place, although these properties can be measured in a quantitative way the possible results of measurement

are not in general any old numbers, but may be restricted to a discrete set of possible 'quantized' values. This discreteness is what gives the new mechanics its name of quantum mechanics. For example, the possible energies for an electron bound in a hydrogen atom are quantized in this way (Fig.1).

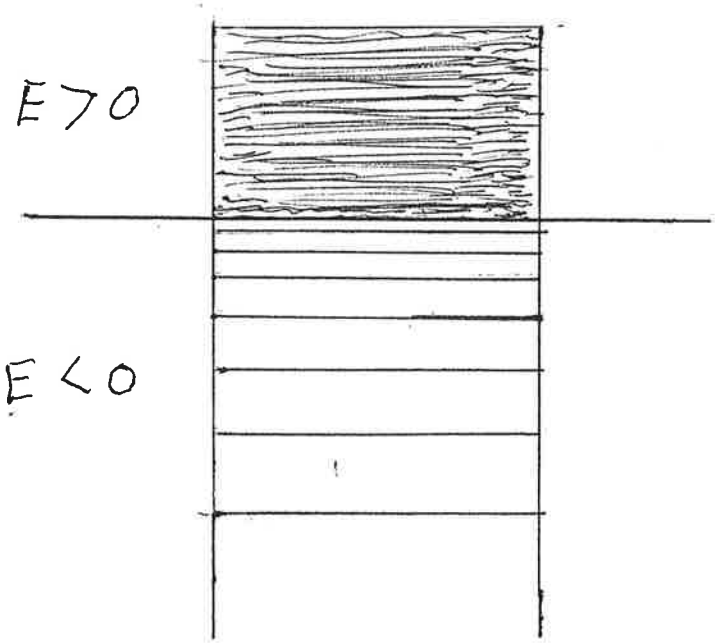

Fig.1

There is a ground state and then excited states. The discrete spectral lines radiated by hydrogen arise as the electron jumps from one energy level to a lower one, emitting the released energy as a photon of radiation.

But there is a second queer feature. The state of a particle in quantum mechanics does not, in general, allow us to predict what the result of measuring some physical magnitude will be, but only the probability that one value will turn up rather than another. Quantum mechanics provides a set of rules for calculating these probabilities for all states and all physical magnitudes, together with further rules telling us how the state and the associated probabilites vary with time.

So far we have talked about the probabilities of measurement results. But what can we say about the magnitudes when they are not being measured? This is the central question posed for the interpretation of quantum mechanics. The traditional answer of the so-called Copenhagen interpretation is that the physical magnitudes are not even defined except in the context of an experimental arrangement appropriate to measuring them. But this raises severe problems about the status of the physical description of the measuring apparatus itself. Put bluntly, should not that only be well-defined in the context of measuring the measuring apparatus and so on in a potentially infinite regress, that may only terminate when the measurement result registers in the consciousness of a human observer. Another view is that something is always well-defined, but it is not in general the value of a magnitude, but the potentiality or propensity to produce one of a range of possible values when measurement is undertaken. On this view measurement consists in actualizing possibilities or potentialities. But again there is a fundamental problem associated with the fact that the formalism of quantum mechanics allows macroscopic objects like cats or tables to exist in states of potentiality rather than actuality for observables like being alive or dead for the cat, or the table being located here or at the other side of the room!

To escape these sorts of problems much the most straightforward approach would be to assume that all magnitudes in all states possess sharp precise values just as in classical physics, which are simply revealed by measurement, so there are no mysteries like Schrödinger's dead and alive cat. The probabilities in the quantum-mechanical formalism are epistemic, just measuring our ignorance of what the precise state of affairs actually is. So could quantum mechanics be interpreted as just a sort of glorified statistical mechanics?

In 1935 Einstein, Podolsky and Rosen produced a famous argument, suggesting that this might indeed be the case. They considered, in essence, a 'black box' (see Fig. 2) producing pairs of particles in a state where quantum mechanics could only predict probabilities for the outcomes of measurements of appropriately chosen properties for the individual particles. There is another feature of the experiment we need to know. Measurements of the same property on the two particles are exactly correlated. Let us represent the two particles by two red discs, the colour indicating the property we are discussing, and let the outcome of measurement of this 'red' property have two possible (quantized) values +1 and -1. Then the correlation property for the two particles, I just mentioned, means that the pair is (R+,R+) or (R-,R-), where the notation indicates red=+1 for the left-moving particle with red=+1 for the right moving-particle, and similarly for the red=-1 correlation. But, aside from the correlation, an important feature of the experiment is that the measurement results for an individual particle are distributed quite randomly.

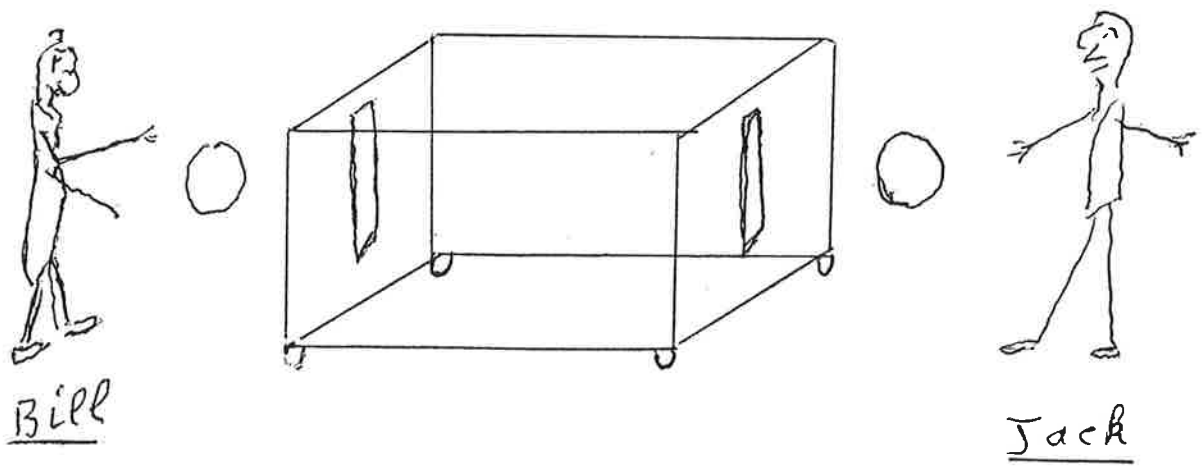

Fig.2

So, I now want to prove to you that even though quantum mechanics only prescribes a probability for getting red=+1, for the left-moving particle and a complementary probability for getting red=-1, that nevertheless the left-moving particle does in fact possess one or other of these two values before we actually look to see which it is. Mutatis mutandis we can make the same claim for the right-moving particle, but let us concentrate for the moment on the case of the left-moving particle.

I know that if at some time $t_1 > t_0$, the time when the particles are produced by the box, I look at the right-moving particle, then I have put myself in a position to predict at any time $t_2 > t_1$ whether the left-moving particle is + or -. Thus suppose I look at the right-moving particle and see that it is +, then I know that, if I look at any subsequent time at the left-moving particle it will also show +, and vice versa if the right-moving particle had shown - . Now Einstein claimed that accurate prediction of this sort could only be expected if there was what he called an 'element of reality' associated with the predicted value, and revealed by the subsequent observation. It is just the same argument as that tables really exist when I turn my back. I can predict reliably that I will see them again when I look again (assuming no outside interference like the broker's men removing the table when my back was turned). Of course Einstein's sufficient condition for identifying elements of physical reality is a metaphysical assumption, famously denied by Bishop Berkeley for example. But give or take the odd idealist in the audience, I expect you will all feel able to go along with Einstein's argument up to this point.

So at this point we have proved the existence of a definite value for the red property of the left-moving particle at any time subsequent to t_1, when we inspected the right-moving particle. But now, queries Einstein, what can we say about the value for the left-moving

show 2a

particle for times between t_0 and t_1? There are two alternatives, either the definite value existed throughout this period, or, it did not exist prior to t_1, but was brought into existence by some spooky action-at-a-distance originated by the event of our looking at the right-moving particle. Einstein totally rejected this second alternative and hence concluded that the definite value existed at all times since the emission from the box.

But now the argument takes on an extraordinary and ironic twist. I shall show that the very same black box that Einstein used to demonstrate the existence of definite values for the properties, assuming no spooky action-at-a-distance, can be used to demonstrate that spooky action-at-a-distance must actually take place.

Schematically,

no-action-at-a-distance
⟶ possessed values
⟶ action-at-a-distance

and the conclusion from that argument by straight logic is that there is spooky action-at-a-distance. And had Einstein lived to learn of this result, which was not discovered until 1964 by John Bell, he would not have been at all pleased, since his most famous creation, relativity theory, was also predicated on the impossibility of transmitting instantaneous effects at a distance!

But before jumping ahead to discuss the implications of this extraordinary state of affairs, let me go through a version of Bell's argument, which I have developed especially for this lecture. The idea is to consider two properties for each of the particles instead of just one as in the original Einstein argument. So we will consider a red and a green property for the left-moving particle, and a blue and a yellow property for the right-

moving particle. Since we are considering different properties for the two particles we no longer have the perfect correlations of the Einstein argument, but nevertheless there will be some quite specific, less than perfect correlation, for the pairs of results for each of the four 'colour ways', red-blue, red-yellow, green-blue and green-yellow, that can be calculated quite explicitly by the rules of quantum mechanics. To be more specific, suppose we consider N pairs of particles, and let the number of ~~particles~~ pairs in the red-blue colour way with the ~~results~~ values + and + be denoted by N(R+,B+) and similarly for all the 16 ways of cordinating the 4 possible pairs of outcomes for each colour way, with the 4 colour ways.

Then clearly

$$
\begin{aligned}
& N(R+,B+)+N(R-,B-)+N(R+,B-)+N(R-,B+) \\
+\quad & N(R+,Y+)+N(R-,Y-)+N(R+,Y-)+N(R-,Y+) \\
+\quad & N(G+,B+)+N(G-,B-)+N(G+,B-)+N(G-,B+) \\
+\quad & N(G+,Y+)+N(G-,Y-)+N(G+,Y-)+N(G-,Y+) \\
=\quad & 4N \qquad\qquad (1)
\end{aligned}
$$

Now suppose we change some of the signs so as to subtract some of the terms on the L.H.S. of Eq.(1). The result must be $\leq$ 4N? But now I raise the question. Can we judiciously juggle the + and - signs on the L.H.S. of (1) so that we can tighten the bound below 4N? The answer is 'Yes'. I will now demonstrate to you that the following expression (in which I have rearranged the order of the terms so as to start with all additions followed by all subtractions) is always $\leq$ 2N

$$
\begin{aligned}
& N(R+,B+)+N(R-,B-)+N(R+,Y+) \\
& +N(R-,Y-)+N(G+,B+)+N(G-,B-) \\
& +N(G+,Y-)+N(G-,Y+) \\
& -N(R+,B-)-N(R-,B+)-N(R+,Y-) \\
& -N(R-,Y+)-N(G+,B-)-N(G-,B+) \\
& -N(G+,Y+)-N(G-,Y-) \\
\leq\ & 2N \qquad\qquad (2)
\end{aligned}
$$

In passing you may wonder whether analagous results hold for the general n x n′ case where n is the number of properties considered for the left-moving particle and n′ the number of properties considered for the right-moving particle. It is easy to show that we cannot get anything of this sort for the 1 x 1 case or the 2 x 1 case. The 2 x 2 case is, of course, the one we are considering. For 2 x 3, and 3 x 3, etc., some interesting results have been obtained using the powerful methods of linear programming and convex analysis, but this is a topic that is currently under active investigation, and serves to demonstrate how a particular result apparently 'discovered' by a physicist, can often be located in an esoteric, but essentially well-known mathematical framework. ← show (5) go to explanation

To return to our main task, I will prove (2) to you by actually doing the experiment, trying a few pairs of particles, and seeing how things turn out.

Roll So here comes the first pair of particles. It has R+ and G- for the left-moving particle and B- and Y+ for the right-moving particle. So we fill in the first row of Table 1. We note that for this one trial the L.S.H. of (2) is just 2, so the bound has not been broken for N=1.

Roll— Now here comes the second pair of particles. It has R- and G- for the left-moving particle and B+ and Y+ for the right-moving particle. So we can fill in the second row of Table 1.

Adding the two rows gives 0 for the L.H.S. of (2), so again the bound is not broken for N=2. But now we can see how things are turning out. It is easy to check that each row of the table contributes either +2 or -2, whatever the assignment of values to colours, so adding N rows can never get bigger in magnitude than 2N, which is what the inequality (2) says. ← show (4) again

ADD								SUBTRACT							
R+, B+	R-, B-	R+, Y+	R-, Y-	G+, B+	G-, B-	G+, Y-	G-, Y+	R+, B-	R-, B+	R+, Y-	R-, Y+	G+, B-	G-, B+	G+, Y+	G-, Y-
		✓			✓		✓	✓							
							✓		✓		✓		✓		

Table 1.

But now let N get very large (tend to infinity). Then $N(R+B+)/N \rightarrow Prob(R+,B+)$, the probability of getting outcomes + and + for the red-blue colour way, and so on for all the 16 terms in (2). So we end up with the result

show (6)

$$
\begin{aligned}
&| \; Prob(R+,B+)+Prob(R-,B-)+Prob(R+,Y+) \\
&+Prob(R-,Y-)+Prob(G+,B+)+Prob(G-,B-) \\
&+Prob(G+,Y-)+Prob(G-,Y+) \\
&-Prob(R+,B-)-Prob(R-,B+)-Prob(R+,Y-) \\
&-Prob(R-,Y+)-Prob(G+,B-)-Prob(G-,B+) \\
&-Prob(G+,Y+)-Prob(G-,Y-) \; | \\
&\leq 2 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (3)
\end{aligned}
$$

But the probabilites are what can be calculated by quantum mechanics, and for appropriate choice of the properties red, green, blue and yellow, the L.H.S. of (3) comes out at $2\sqrt{2}$, in violation of the inequality. The experiments have been done and that is what actually happens. So how can this possibly be? Either the particles do not have the definite values inscribed on them (but the Einstein-Podolsky-Rosen argument shows that they do) or if they do these values must flip, at any rate in some cases, from + to - or - to +, according to which side of the remote particle is being inspected. But that is spooky action-at-a-distance with a vengeance.

show (5) again

go to Experiment:

Liz can show

To illustrate: Here I have a left-moving particle showing R+ and the right-moving particle shows Y+. Now look at the green side of the left-moving particle. It shows G-. Now inspect the blue side of the right-moving particle. It shows B-, with the left-moving particle still showing G-. What does the red side of the left-moving particle show? Could it have flipped to R-, when we changed what we were looking at for the right-moving particle from yellow to blue. Well, I am only a philosopher not a conjuror, so I cannot show that happen with cardboard discs (hold up R- in view of audience, but

Podo Repeats

not of myself!). You need really expensive apparatus, with lasers and photons, to show it happen.

There is another vital piece of the story to add in here. We cannot look simultaneously at both sides of the disc, (This reflects Heisenberg's famous uncertainty principle, which prevents simultaneous measurability of certain quantities in quantum mechanics). If that were not so, we could check the value assignments for all four colours on the two discs and then, whatever these assignments, the inequality (3) would follow. But if we cannot look at both sides simultaneously, then the value assigned to one colour on the left-moving particle, for example, could change if we had looked at the colour on the right-moving particle that we did not actually look at. But expressed in this counterfactual way, are we being committed to action-at-a-distance, if the inequality is violated? That is a slightly ticklish question in the logic of counterfactuals.

Let me try out two examples on you. First, consider a clock at the far side of the room. I raise my hand just as it strikes six o'clock. I now ask the question. "If I had not raised my hand would the clock still have struck?". Assuming no spooky action-at-a-distance, I think you would all agree the answer is "Yes".

But now consider an atom of radium instead of the clock. I raise my hand and it decays at six o'clock. Again I ask "If I had not raised my hand would it have decayed at the same time as it actually did, viz. six o'clock?" It is not clear what the answer should be, if the decay is an intrinsically indeterministic process. I run the world over again up to six o'clock with my hand not raised, but this time the atom might well not decay, not because of any spooky effect of my hand on the atom, but simply because that is what indeterminism means - specifying the world up to six o'clock does not fix what actually happens at six o'clock! Or consider the

conundrum of the indeterministic roulette wheel. I place my bet on No.16 and No.17 turns up. Am I justified, for a genuinely indeterministic roulette wheel, in exclaiming "If only I had placed my bet on No.17, I would have won a fortune!"

All this suggests a way out of our predicament. Just suppose that the +'s and -'s are not fixed on each side of the disk but are varying in an indeterministic or stochastic fashion. Then I could not derive the inequality, and its violation would tell me nothing about action-at-a-distance. But there is a difficulty with this solution. Let us go back to the original Einstein experiment. When I found red=+1 for the right-moving particle, then whenever I look at the left-moving particle it will always show the same value, viz. +1, so the number cannot be changing in the random manner proposed, unless the fact of looking at the right-moving particle changed the behaviour of the left-moving particle so as to fix the subsequent value. But that would be spooky action-at-a-distance, the very thing we are trying to avoid.

show (2) again

So, what can we say about this action-at-a-distance that seems endemic to quantum mechanics, and how can it be reconciled with the theory of relativity?

The first surprising, but very relevant, thing to notice is that the effect we are discussing cannot be used to transmit very fast, even instantaneous, signals. As I put it in my book there is no such thing as a Bell telephone! To see this, consider again the Einstein version of our experiment. Remember that, for the left-moving particle, for example, successive measurements yield red=+1 or red=-1 in a quite random fashion. The long-run frequences are stable, typically 50% for each outcome, but the sequence of outcomes has no pattern or order to it. It might look like + - + - - + - + etc. Now imagine Jack manipulating the right-moving particles.

Can he do anything to inform Bill, who we suppose to be observing the left-moving particles, of what he, Jack, is up to. The answer is "No". All Jack can do is to note whether he is getting red=+1 or red=-1 for his particle on a particular occasion. This enables him to know, instantaneously, what result Bill is going to observe. But that does not change anything for Bill. To achieve a change in the sequence that Bill is observing, Jack would have to transmit his information (using a conventional telephone for example) warning Bill to put an absorbing screen in front of every particle that was going to show red=-1. Then the particles that got through for Bill to look at would all show red=+1, so the original random sequence would have got altered, but not spookily or instantaneously. The solution here is no more mysterious than the fact that when I walked into the lecture theatre at LSE you all learned instanteously that my room at Cambridge was empty! But to use this knowledge to produce a physical change at Cambridge, like preventing students from knocking on my door, would require you to transmit your information, by conventional means, back from London to Cambridge,

In fact it is possible to prove quite generally, from the formalism of quantum mechanics, that there is no way of violating what in my book I called statistical locality, i.e. the impossibility of changing the marginal probabilities for measurement outcomes of any physical magnitude associated with one particle by any operation performed on the other particle.

Now, in relativity theory it is the possibility of transmitting signals at superluminal speeds that is standardly regarded as prohibited. So already we have a clue that the nonlocality we have demonstrated in quantum mechanics may not necessarily violate relativistic considerations. But let us probe this matter further. In standard philosophical discussions of relativity theory it is not signalling as such which is at issue but

rather the impossibility of a causal process propagating itself at superluminal speeds. So what is the connection between causality and signalling? It is generally assumed that causality is a necessary and sufficient condition for signalling. I am going to argue that the connection is, in general, less simple, and needs to be tackled by introducing a necessary condition for causality, which I call robustness.

Show (7)

Consider a spring connecting an object A to a rigid wall B (see Fig. 3).

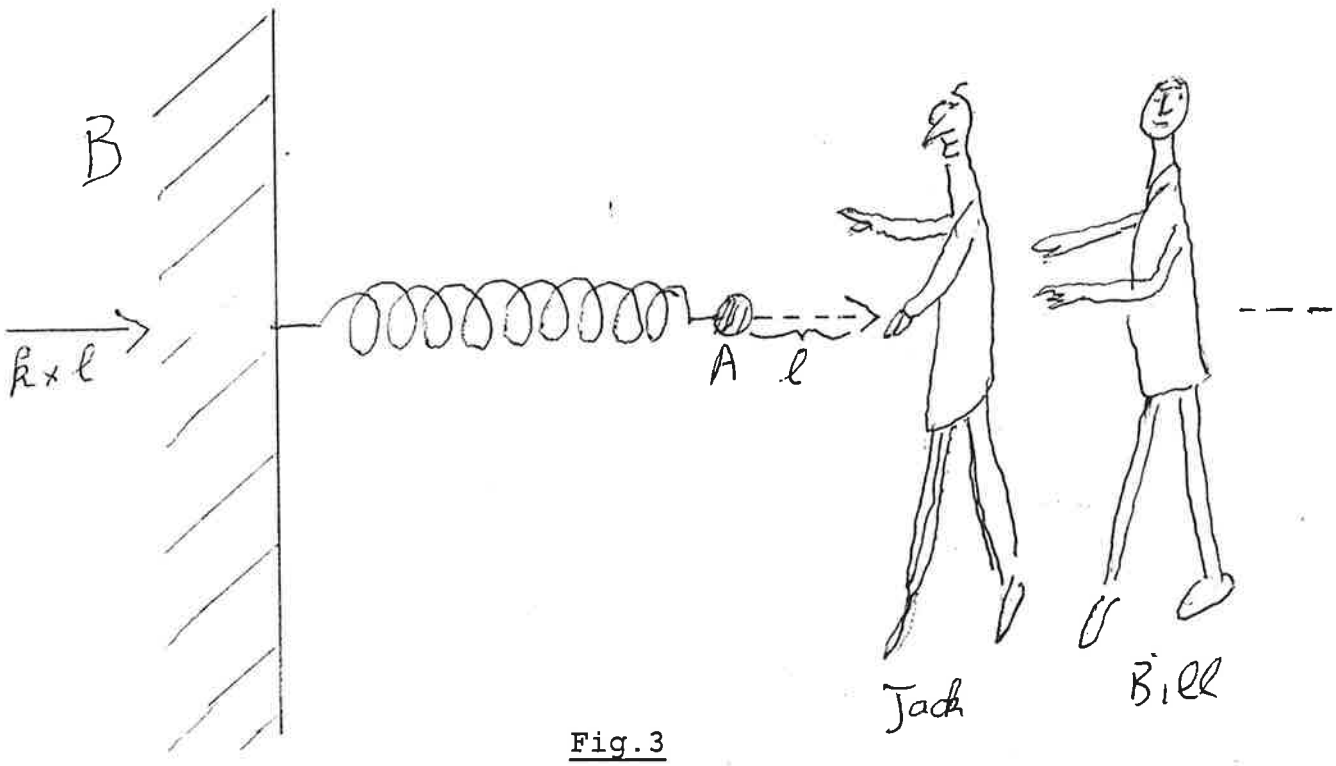

Fig.3

Suppose A is pulled to the right a distance l, then the force exerted on B is k x l where k is a constant, which we will call the spring constant. We may regard the displacement l as the cause of the force k x l (which will be experienced by B at a suitably later time than the displacement of A as the elastic deformation propagates along the spring). The causal connection implies that there is a definite relationship of fixed

mathematical form between the displacement of A and the force on B. In particular, the relationship, characterized by the spring constant k, does not depend on how the displacement l is brought about, for example it does not depend on whether Jack pulls the spring or whether Bill pulls the spring. This invariance property of the causal relation I will refer to as robustness. I claim it is a necessary condition for a causal connection. Suppose, in our example, that the spring constant itself depended on who pulled the spring, then the displacement alone could not be regarded as the cause of the force experienced by B. Of course we could restore the notion of cause by citing not just the magnitude of the displacement, but also who pulled the spring, but suppose this composite cause was again not robust, the spring constant depending on who pulled Jack who pulled the spring and so ad infinitum, then I claim we would be in a marshmallow world, where the notion of cause was no longer applicable. But that does not mean that Jack could not signal. Every time he pulls the object A a distance l, some force is experienced at B, although the magnitude might depend on an infinite regress of all the circumstances that brought about the event of Jack pulling the spring.

So causality $\longrightarrow$ robustness $\longrightarrow$ signalling, i.e. causality is a sufficient condition for signalling, but not a necessary one. This point needs some additional comment. Signalling does not imply a causal relation between displacement and force, but it does imply a causal relationship between certain other physical magnitudes, which I shall refer to as gisplacement and gorse. Gorse has the value zero if the force is zero, and the value one if the force is non-zero. We make a similar definition relating gisplacement and displacement. Then, in our marshmallow world, there is no robust relation between displacement and force, as we have seen, but there is a robust relation between gisplacement and gorse. Filling out the necessary condition of robustness

of non-robustness. Let me give an illustration of what passion is like. Imagine that my two hand are correlated by a stick held between them. As I move my hands around there is a definite correlation, a fixed distance between them. But now suppose that when one of my hands is disturbed, however gently, a new correlation, a new distance between them, is established. Definite correlations are there if I do not poke or disturb the system in any way, but they are too delicate, non-robust as I put it, to reflect a causal connection. This, I believe, is how we should think of the Bell correlations.

Notice the importance of indeterminism in this whole analysis. If there is underlying determinism, I think that there is no plausible way of avoiding the conclusion that superluminal causal action is at work in the Bell experiments, not indeed between events consisting of physical magnitudes taking values, but linking the value of a physical magnitude for one particle to the experimental environment confronting the other particle. Notice that this does not conflict with the formal no-signalling theorem, which is a statistical result and does not apply to what happens on a particular occasion. Moreover note that observation on a single pair of particles cannot be used to signal, since it can be shown that as soon as we inspect the state of one particle, the causal influence of the remote environmental context becomes inoperative.

Passion suggests that the two particles are to be thought of as, in some sense, a single 'whole', rather than as two separate entitites. A substantial part of my book was concerned with developing in other ways the distinction between particles with individual properties, having these properties affected instantaneously and spookily at a distance, and the idea that the particles do not really have individual properties at all, but only relativized to a holistic context. Such holistic ideas have been invoked previously by authors such as Niels

with features of constant conjunction, contiguity and temporal succession allows us to infer a causal connection between gisplacement and gorse.

From the foregoing discussion, we now have the following implications: no-signalling $\dashrightarrow$ non-robustness $\longrightarrow$ absence of causality, for any conceivable pair of magnitudes. So can our no-signalling result in the quantum-mechanical case be used to infer the absence of a causal connection, and hence defuse the putative conflict with relativity.

I fear not, because the argument so far has been predicated on determinism. The question of probabilistic causality involved in maintaining correlations between essentially indeterministic events is a more delicate one. I will merely state my conclusions on this question. Again we have causality $\longrightarrow$ robutness, but now in general robustness $\not\longrightarrow$ signalling. (To be more precise this arises when the signalling perturbations do not allow sufficiently arbitrary control over the local marginal probabilities, a fairly typical situation in quantum mechanics). So we cannot infer the absence of probabilistic causality from the no-signalling theorem. A separate investigation is necessary to check whether the correlations in the Bell experiment do or do not satisfy the appropriate technical definition of robustness. Suffice it to say that in my book I demonstrated by direct calculation that the Bell correlations were non-robust and hence were not being maintained by a direct causal relationship between events consisting of physical magnitudes for the two particles taking values.

Transk in mechanics

So how are we to understand the mysterious Bell correlations? Abner Shimony has coined the phrase 'passion-at-a-distance' to capture the harmonious behaviour of the separated particles in the Bell experiment. In my own work I have tried to flesh out this idea with some mathematical precision via the notion

Bohr and David Bohm in the context of understanding quantum mechanics. But my own work has differed from theirs in trying to provide a precise mathematical framework in which to express such ideas and draw the relevant distinctions. I believe that that is the way forward in trying to get a grip on the implications of modern physics for the metaphysical nature of reality.

Let me conclude by quoting from a famous Princeton philosopher, writing in 1986 in the preface of vol.2 of his collected papers. "I am not ready to take lessons in ontology from quantum physics as it now is. First I must see how it looks when it is purified of instrumentalist frivolity and dares to say something not just about pointer readings but about the constitution of the world; and when it is purified of doublethinking deviant logic; and - most of all - when it is purified of supernatural tales about the power of the observant mind to make things jump." I submit that much of that work has in fact now been done and that philosophers should stand ready to evaluate the results.